AD-A277 097

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(2)

1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE March 8, 1994 | 3. REPORT TYPE AND DATES COVERED Reprint

4. TITLE AND SUBTITLE

Current Collection and Ambient Plasma Measurement During Electron Beam Emission at Near Geosynchronous Altitudes

5. FUNDING NUMBERS

PE 62010F
PR 7601
TA 30
WU 06

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8. PERFORMING ORGANIZATION REPORT NUMBER

PL-TR-94-2046

Reprinted from AIAA 94-0370 32nd Aerospace Sciences Meeting & Exhibit January 10-13, 1994 Reno NV

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14. SUBJECT TERMS	15. NUMBER OF PAGES
Spacecraft charging, Spacecraft interactions, Electron beam, Ion beam, Geosynchronous, SCATHA	6
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

PL-TR-94-2046

AIAA

AIAA 94-0370
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32nd Aerospace Sciences Meeting & Exhibit
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Current Collection and Ambient Plasma Measurement during Electron Beam Emission at Near Geosynchronous Altitudes

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ABSTRACT

This paper discusses spacecraft interactions during electron beam emissions from a spacecraft rotating in sunlight. We present an improved Langmuir probe equation for the current collection by the SCATHA satellite. The equation yields results on ambient plasma density and temperature. The results compare favorably with the very few measurements obtained by other methods on the elusive ambient plasma at near geosynchronous altitudes.

INTRODUCTION

Spacecraft potentials float with respect to the ambient plasma. During electron beam operations, a spacecraft's potential varies in response to the emitted current. At equilibrium, the spacecraft potential and the ambient current collected are related by Langmuir's plasma probe equation. In the laboratory, the current collected by a Langmuir probe varies according to the applied potential. In space, however, the current is the driving force and the probe potential is the response.

In ideal geometries, such as a sphere or an infinitely long cylinder, the equation is well known. The geometry for most spacecraft, however, is neither a sphere nor an infinite cylinder. For improved spacecraft charging modeling, it is better to determine and use the correct Langmuir probe equation rather than taking an ideal geometry equation as commonly practiced.

The determination of the Langmuir probe equation for a given spacecraft requires data of ambient current and spacecraft potential. This is often difficult because the current data often represent the sum of currents of different processes and the potential may be due to some complex causes. For example, when a spacecraft is rotating in sunlight [*Lai, et al*, 1986], photoelectrons leave the satellite surfaces. When electron beams are emitted from a spacecraft, photoelectron generated from the boom surfaces may return to the spacecraft body [*Lai, et al*, 1987; 1989]. Magnetic storms can affect spacecraft potential but storms fluctuate and are very complex.

In this paper, we determine an improved Langmuir probe equation for the SCATHA satellite by taking the current voltage data taken on Day 70, 1981 on the satellite. SCATHA was launched in 1979 for the purpose of spacecraft charging studies. Its shape was a short cylinder. Its length was about 0.8 m and so was its diameter. Its altitude was near geosynchronous. It was equipped with two 50 m booms (SC10) deployed oppositely in the equatorial plane. The "tip", farther out 20 m, of each boom was coated with copper beryllium (CuBe) [*Aggson, st al*, 1983]. The booms are electrically isolated from the satellite body. SCATHA rotated perpendicular to sunlight at about once per min.

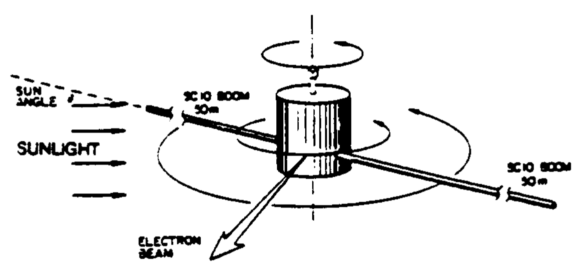

Figure 1. The SCATHA satellite and its SC10 booms.

We choose Day 70 for the following reasons. The environment was quiet. During the period chosen, SCATHA emitted an electron beam at a constant energy, 300 eV, with the beam current, I_b, increasing continuously. As beam electrons left, the spacecraft potential, ϕ_s, increased and therefore ambient electrons came in to balance the current. The potential was governed by the balance of currents. In this situation, the varying beam current was the known driving force while the satellite potential was a response.

We first identify the various physical processes occurring during the electron emissions. We then use the data of the Langmuir probe regime to dete..nine an improved formula.

CURRENT-VOLTAGE DATA

The SC10 potential ϕ_{SC10} is given by

$$\phi_{SC10} = \phi_b - \phi \qquad (1)$$

which is the difference between ϕ_b, the potential of the tip of a boom, and ϕ, the spacecraft potential. The boom material has high secondary emission. Therefore, when the environment is quiet and there is no severe charging, the ϕ_b is near the ambient plasma potential (i.e. $\phi_b \approx 0$, and $\phi_{SC10} \approx -\phi$).

Figure 1 shows the satellite and its booms in sunlight. Figure 2 shows the oscillating ϕ data taken during the electron beam emission period. The electron beam energy was 300 V constantly. The satellite was rotating perpendicular to the direction of sunlight with the booms in the equatorial plane. The booms subtended an angle θ with sunlight. $\theta = 0^o$ or 180^o when the booms were parallel to sunlight. The data dropouts were due to calibrations.

The maxima of the amplitude $|\phi|$ occurred when the booms were parallel to sunlight ($\theta = 0^o$ or 180^o) and the minima at $\theta = 90^o$ or 270^o. Both the average potential ϕ and the amplitude of oscillation $|\mathrm{Max}\,\phi - \mathrm{Min}\,\phi|$ increased as the beam current increased.

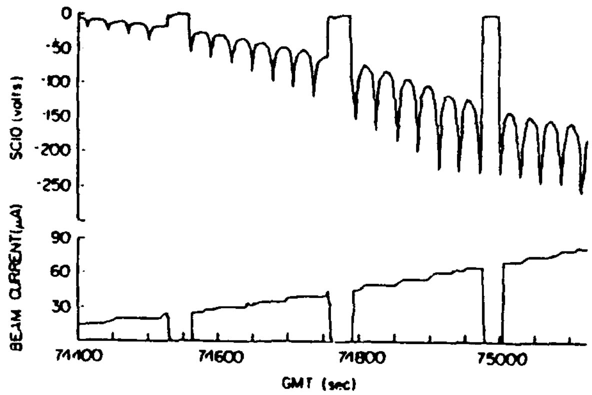

Figure 2. The SC10 potential and beam burrent data.

THEORETICAL INTERPRETATIONS

The spacecraft potential ϕ is determined by the balance of currents according to Kirchhoff's law. In the Langmuir probe model, the currents are balanced as follows:

$$\mu I_e(0)\left(1+\frac{e\phi}{kT}\right)^{\alpha} - I_i(0)\exp\left(-\frac{e\phi}{kT}\right)$$

$$(2) \qquad - I_b - I_r + I_{ph,s} + I_s - I_{ph}$$

for $e\phi > kT$. In eq(1) $I_e(\phi=0)$ and $I_i(\phi=0)$ are the ambient electron and ion currents collected at $\phi=0$, T the ambient plasma temperature, I_b the beam current, I_r is the returning beam current, I_s the secondary electron current, $I_{ph,s}$ the photoelectron current from the spacecraft body and I_{ph} the photoelectron current from the booms to the spacecraft body. $\mu = 1$ for a spherical spacecraft and $2/\pi^{1/2}$ ($\approx$1.1) for an infinite cylindrical spacecraft. The ambient ion current I_i is usually two orders of magnitude smaller than I_e [*Reagan, et al.*, 1980]. Therefore $I_i(\phi)$ is negligible unless ϕ reaches thousands of Volts negative. In eq(2), ϕ is positive and increases as the electron beam current I_b increases.

We contend that the oscillatory behavior of the potential ϕ (Fig.2) is due to the modulation by the photoelectron current I_{ph} from the booms to the satellite body. The booms were near ambient potential while the satellite body was at a positive potential during beam emissions. As the satellite potential ϕ increased, the potential sheath extended to engulf part of the booms. Let I_T be the total photoelectron current generated from the booms. The fraction of I_T going away to the ambient plasma depends on the extent of boom engulfment (Figure 3). When $\theta = 0^o$ or 180^o, $I_{ph} = 0$; when $\theta = 90^o$ or 270^o, I_{ph} was maximum.

MATHEMATICAL MODELING

We now derive I_{ph} and f. Figure 3 shows the geometry of the boom angles. The angle Θ between the sunlight unit vector $s_1 = (\cos\theta, \sin\theta, 0)$ and a boom radius unit vector $\rho_1 = (0, \cos\varphi, \sin\varphi)$ is given by

$$s_1 \cdot \rho_1 = \cos\Theta = \sin\theta\cos\varphi \qquad (3)$$

For a surface area dA, the effective sunlit area is dA $\cos\Theta$, where $dA = \rho\ dr\ d\varphi$ and r is the distance along a boom.

$$I_{ph} = \int_0^L dr \int_{-\pi/2}^{\pi/2} d\varphi\, r \sin\theta \cos\varphi\, j_{ph}(\theta,\varphi) f[\phi(r)] \qquad (4)$$

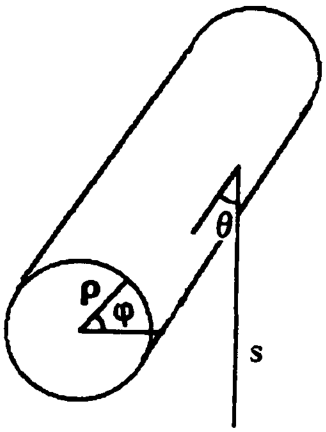

Figure 3. Geometry of the boom angles.

where $j_{ph}(\theta,\varphi)$ is the photoemissivity of CuBe, the boom surface material, and L the length of a boom. In terms of surface reflectivity R [*Lai, et al.*, 1986], $j_{ph}(\theta,\varphi)$ can be written as

$$j_{ph}(\theta,\varphi) = j_{ph}(90^\circ,0^\circ)[1 - R(\theta,\varphi)] \qquad (5)$$

Since $j_{ph}(\theta,\varphi)$ of the booms has not been measured, we assume a constant j_{ph}, which is to be determined. If both j_{ph} and f are constants, eq(4) becomes

$$I_{ph} = 2 f r L j_{ph} \sin\theta \qquad (6)$$

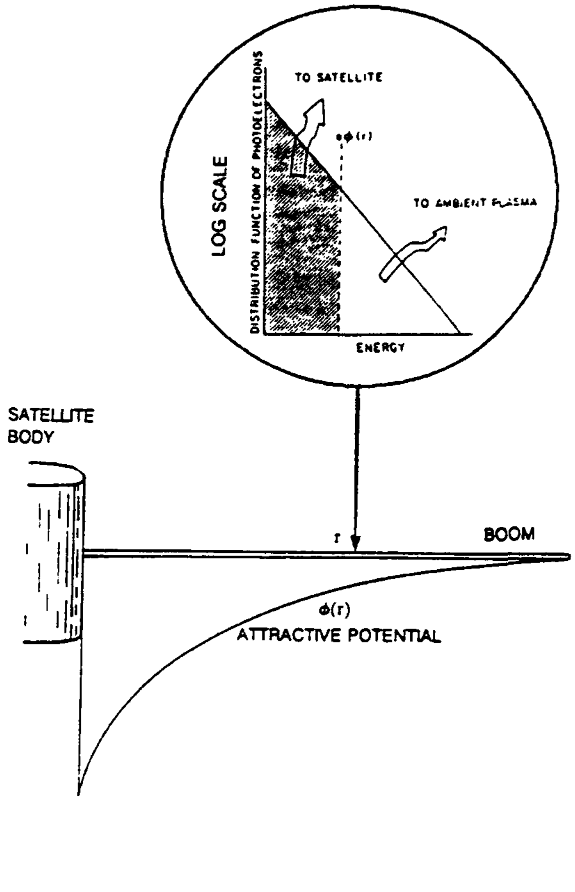

Figure 4. Sheath engulfment and the photoelectron energy partition function.

We now calculate $f[\phi(r)]$. By means of the partition of the photoelectron energy distribution function (Figure 4) at distance r along a boom, the fraction f is given by

$$f = 1 - \frac{\int_{e\phi}^{\infty} dE\, E \exp(-E/kT_{ph})}{\int_{e\phi}^{\infty} dE \exp(-E/kT_{ph})} \qquad (7)$$

where we adopt the Debye form [*Whipple, et al.*, 1974] for the satellite sheath potential $\phi(r)$:

$$\phi(r) = \phi(0)\frac{R_s}{r+R_s}\exp(-r/R_s) \qquad (8)$$

where R_s is the radius of the satellite body and $\phi(r=0)$ is the satellite potential ϕ (eq.2). We integrate eq(7) to obtain a handy formula of the fraction f of the boom photoelectron current going away into the ambient plasma:

$$f[\phi(r)] = 1 - \left(1+\frac{e\phi(r)}{kT_{ph}}\right)\exp\left(-\frac{e\phi(r)}{kT_{ph}}\right) \qquad (9)$$

which appears in the integral (eq.4). In eq(9), when $\phi \rightarrow 0$, $f \rightarrow 0$; when $\phi \rightarrow \infty$, $f \rightarrow 1$ properly. Using the above model, *Lai* [1994] has fitted the ϕ data of Figure 2 and obtained j_{ph} = 3.5 nanoamp/cm^2, which agrees with the estimate of *Kellogg* [1980].

LANGMUIR PROBE FORMULA

We now choose the potential ϕ data when θ = 0° or 180°. Since I_{ph} = 0 at these moments, there is no photoelectron current involved.

Three regimes can be identified in Figure 4. In Regime I, the spacecraft potential is low. Therefore, photoelectrons and secondary electrons can leave the spacecraft body. In Regime III, the spacecraft potential is near the beam energy. Therefore, beam saturation and partial beam return can occur.

In Regime II, there is no photoelectron or beam return. In this regime, the Langmuir probe formula (eq.2) becomes

$$\mu I_e(0)\left(1+\frac{e\phi}{kT}\right)^{\alpha} = I_b \qquad (10)$$

where α, $I_e(0)$, kT, μ (between 1 and 1.1), and α (between 1 and 0.5) are to be determined. In eq(10), when ϕ=0, we have $I_e(0) \approx I_b$. Therefore, extrapolating the I-V curve to ϕ=0, we obtain the ambient plasma current $I_e(0) \approx 10\ \mu$A during the quiet period. This $I_e(0)$ result agrees with the statistical result of *Purvis et al.* [1984].

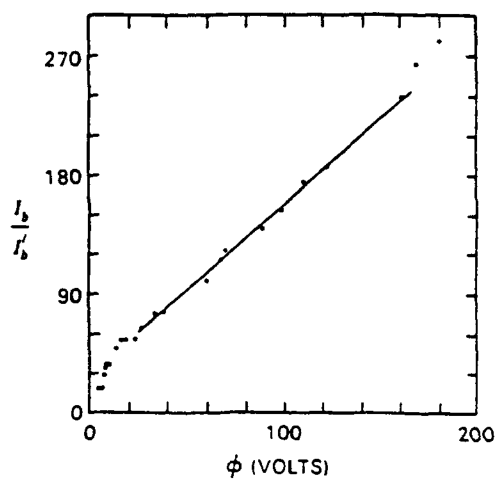

Figure 5. Solution of eq(11).

To determine the exponent α (eqs 2,10) and the ambient plasma temperature kT, we first obtain I_b', the differentiation of I_b by $e\phi$ (Figure 5).

$$\frac{I_b}{I_b'} = \frac{1}{\alpha}(kT+e\phi) \qquad (11)$$

From the slope, $1/\alpha$, and the intercept, kT/α. we obtain $\alpha \approx 0.775$ and kT $\approx$ 23.2 eV.

To determine the ambient plasma density n_e, we write down the current intercepted by the spacecraft body when ϕ = 0.

$$I_e(0) = \frac{1}{4}n_e V_e D = 10\mu A \qquad (12)$$

where D is the cross sectional area of the satellite body, V_e the electron velocity which depends on kT. Using the known values D and kT, we obtain $n_e \approx 8.47\ cm^{-3}$.

If value of $I_e(0)$ ($\approx 10\ \mu A$) is accurate and agrees with measurements by other instruments, we can determine μ by taking the log of eq(10).

$$\log I_b = \alpha \log\left(1 + \frac{e\phi}{kT}\right) + \log\mu + \log I_e(0) \qquad (13)$$

A plot of $\log_{10}(I_b)$ versus $\log_{10}(1+e\phi/kT)$ yields an intercept ≈ 1 and a slope ≈ 0.775 in Regime II (Figure 6'). Therefore we obtain $\mu \approx 1$ and $\alpha \approx 0.775$.

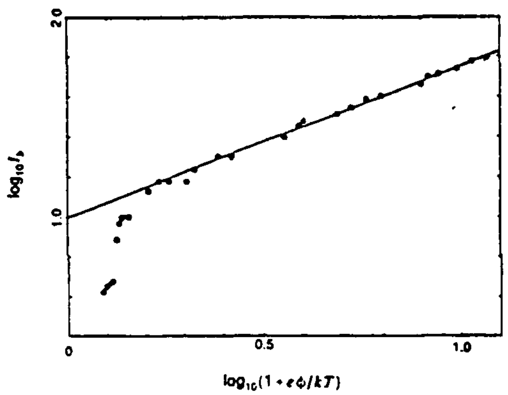

Figure 6. Solution of eq(13).

SUMMARY AND DISCUSSION

By modeling the various processes occurring during a period of electron beam emission on Day 70, 1981, we have identified a regime, which is properly described by a Langmuir probe model (eq.10). In this regime, the electron beam current controls the spacecraft potential without beam return or photoelectrons involved. We have determined the parameters in the Langmuir probe equation by fitting the data in this regime.

The results obtained are (1) the boom surface photoemissivity $j_{ph} \approx 3.5$ nanoamp/cm^2, (2) the ambient plasma current $I_e(\phi=0) \approx 10\ \mu A$, (3) the Langmuir probe formula exponent $\alpha \approx 0.775$, (4) the Langmuir probe multiplicative factor $\mu \approx 1$, (5) the ambient plasma temperature $kT \approx 23.2$ eV, and (6) the ambient plasma density $n_e \approx 8.47\ cm^{-3}$.

The results compare favorably with the very few published ones obtained by other methods. The j_{ph} result agrees with the estimate of *Kellogg* [1980]. The $I_e(0)$ result agrees with the statistical average of *Purvis et al.* [1984].

No other author has reported a method of calculation of α for spacecraft and therefore there is no comparison. Our α result (0.775) is between 1 and 0.5, corresponding to a sphere and an infinite cylinder respectively. Since SCATHA is a short cylinder with about the same height as its diameter, the α result seems reasonable.

Again, no one else has determined μ for a spacecraft, so there is no comparison. Since μ should be between 1 and 1.1, corresponding to a sphere and an infinite cylinder respectively, our μ value (≈ 1) seems reasonable.

Whipple [1981] has reported $kT \approx 64$ eV at the geosynchronous environment during a quiet period. Since the environment is unknown, our plasma temperature kT result seems reasonable. *Higel and Lei* [1984] used ralaxation sounding to obtain an ambient plasma density $n_e \approx 3$ to $7\ cm^{-3}$ at 6.6 R_E, 0500LT and $\Sigma K_p = 13$. SCATHA was at 7.3 R_E, 0500LT, and $\Sigma K_p = 14-$. Our ambient plasma density n_e ($8.47\ cm^{-3}$) is comparable on the high side.

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